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Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT-(29-1)-789

Printed August 1976

Sandia Laboratories
energy report

-QQB(3-74)

Issued by Sandia Laboratories, operated for the United States Energy Research and Development Administration by Sandia Corporation.

Printed in the United States of America

Available from:
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $5.00; Microfiche $2.25

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DISTRIBUTION OF DIRECT AND TOTAL SOLAR RADIATION AVAILABILITIES FOR THE USA*

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ABSTRACT

The only long-term US solar radiation data base with reasonable geographic coverage is the total-horizontal data recorded by the National Weather Service. Since most solar collectors will not be horizontal, designers will need to know the availabilities of solar radiation to different types of both flat-plate and concentrating collectors in various orientations. A project to determine the geographic distributions of these availabilities by month on a mean daily basis is in progress. The data base consists of hourly total-horizontal readings for 26 US locations for the years 1958-1962. This paper presents maps and tables showing the availability of direct-normal radiation by month for the US. The results indicate that there is more direct solar energy than has been generally believed; direct-normal radiation availability generally exceeds total-horizontal availability by about 60% in the winter. Availabilities to other surfaces will be described in the final report to be published at the conclusion of this project.

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* This work sponsored by US ERDA.

Introduction

During the past several years of rapidly increasing activity in solar energy, one of the most frequently posed questions has been that of the amount of solar radiation available to various types of collectors. For instance, do focusing collectors intercept more energy than fixed, flat-plate collectors? How effective for Winter heating is a horizontal collector? A South facing vertical collector? Is there enough direct radiation for solar electric power stations anywhere but the Southwest? Are focusing collectors practical anywhere but in the Southwest?

Fortunately, the National Weather Service has been operating a reasonably extensive solar radiation monitoring network since about 1950. However, since almost all of the measurements were of total (direct + diffuse) radiation on a horizontal surface, these data records do not directly provide the solar energy input information applicable to the variety of solar system designs being studied. Particularly serious have been the questions of the amount direct radiation available and the geographic distribution of solar energy, especially in the Winter. That maps showing only the availability of total-horizontal radiation can be seriously misleading was indicated by a study of Mingenbach's released in 1975 [4].

The present study is directed toward attempting to resolve these basic questions by computing solar radiation availabilities on a monthly or seasonal basis to different types of collectors in various collector schemes. Completely accurate resolution, unfortunately, is not possible at this time because of limited input data and questionable data accuracy. It is hoped that the conclusions of this study will be refined by similar efforts using better data in the future.

I. Computational Procedure

The solar data base for this study consists of all hourly solar data which was available for the five years, 1958 through 1962, from the National Climatic Center, Asheville, NC. Table 1.1 lists the locations and approximate periods of record; sufficiently complete data records were available from a total of 26 stations.

TABLE 1.1

Hourly Solar Data Base Locations and Periods of Record

Location	Period of Record
Albuquerque, NM	All
Appalachicola, FL	All
Bismark, ND	All
Blue Hill, MA	All
Boston, MA	All
Brownsville, TX	All but May-July 1958
Cape Hatteras, NC	All
Caribou, ME	All
Charleston, SC	All
Columbia, MO	All
Dodge City, KA	All but Feb-July 1959
El Paso, TX	All
Ely, NV	All
Fort Worth, TX	All
Great Falls, MT	All
Lake Charles, LA	All
Madison, WI	All but Sept '58-Jan '59, Feb-Sept '60
Medford, OR	All
Miami, FL	All
Nashville, TN	All but Dec 1962
New York, NY	All but Oct '61 - Dec '62
Omaha, NB	All
Phoenix, AZ	All
Santa Maria, CA	All
Seattle, WA	All
Washington, DC	All

The original data tapes contained numerous data gaps, erroneous values, and data out of chronological order. Consequently, the data was edited, sorted, and "filled" before analysis. Data gaps no longer than one day were filled by interpolation; larger data gaps were omitted in subsequent analysis. It is known that these total horizontal solar radiation measurements contain some errors due to faulty calibration, instrument response drift, etc. However, no attempt was made to correct the data because the necessary station-instrument records were not available.

Hourly values of direct-normal radiation, DN, were computed using the recorded measurements of total-horizontal radiation, TH, and the formula,

$$DN = \begin{cases} 0, & \text{if } \underline{PP} \leq .30 \\ -.52 + 1.80\underline{PP}, & \text{if } .30 < \underline{PP} \leq .85 \\ M, & \text{if } PP > .85 \end{cases}$$

The symbol PP is the hourly percent of possible, that is, the total-horizontal reading divided by the computed value of radiation on a horizontal surface above the earth's atmosphere; the units for DN are $kW \cdot hr/m^2$ per hour. This relation was obtained empirically from 1962 National Weather Service data from Albuquerque, Blue Hill, and Omaha. Both direct-normal and total-horizontal radiation data is available for these three locations. Statistical regression techniques were used on these data to relate DN to TH and hence to PP. The above relationship was found to fit the data quite well. Further details of this work can be found in [1]. This relationship is similar to one suggested by Jordan and Liu [2]. Different values for M were used for different months, ranging from .95 in July to 1.05 in January. These are reasonable maximum values for direct-normal radiation; they prevent the difficulty of generating unreasonably high DN values from high PP values caused by such phenomena as concentration of radiation by clouds. Similarly, DN is set equal to 0.4 in those cases of low sun angle when PP is enhanced by bright clouds; the criterion for this is ELEV $< 10^\circ$ and $\underline{PP} > .50$.

Mean daily totals of direct-normal solar radiation were calculated by month for each location by simply summing the hourly values for each day in that month

TABLE 1.2

MEAN DAILY TOTALS OF DIRECT-NORMAL
AND TOTAL-HORIZONTAL RADIATION FOR JANUARY - JUNE

	Jan			Feb			March			April			May			June		
	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N
Albuquerque	6.6	3.6	152	6.9	4.5	139	7.8	5.9	155	8.9	7.3	148	9.9	8.3	155	10.0	8.6	150
Appalachicola	4.7	3.3	142	5.2	4.2	139	5.5	4.9	155	6.6	6.2	150	7.1	6.9	155	6.9	6.8	140
Bismark	4.3	1.8	153	5.4	2.9	141	5.9	4.0	155	7.1	5.4	150	7.3	6.3	155	8.8	7.1	150
Blue Hill	3.6	1.9	134	3.9	2.6	141	4.8	3.8	150	4.9	4.5	113	5.7	5.6	155	5.6	5.7	146
Boston	3.2	1.8	155	3.6	2.5	141	4.8	3.8	149	4.8	4.5	149	5.9	5.6	155	5.9	5.9	150
Brownsville	3.3	2.9	155	4.0	3.7	141	3.9	4.3	155	4.8	5.3	142	6.1	6.3	124	6.4	6.5	119
Cape Hatteras	5.0	3.1	155	5.0	3.7	141	5.9	4.9	155	7.4	6.6	150	8.4	7.6	155	7.5	7.2	135
Caribou	3.9	1.7	155	4.8	2.7	141	6.2	4.2	155	5.6	4.8	150	5.8	5.5	155	6.0	5.7	150
Charleston	3.9	2.7	155	4.3	3.4	141	4.8	4.4	155	6.5	6.0	142	6.4	6.5	155	5.7	6.1	150
Columbia	3.9	2.3	151	4.2	3.0	141	4.3	3.7	155	5.4	5.0	150	6.8	6.4	155	6.8	6.6	150
Dodge City	6.0	3.1	135	4.8	3.3	81	5.9	4.6	115	6.8	5.9	112	7.5	6.8	124	7.9	7.2	108
El Paso	6.6	3.8	155	7.5	5.0	141	8.6	6.4	155	9.6	7.8	150	10.2	8.5	155	9.8	8.5	150
Ely	5.5	2.9	155	5.4	3.6	141	7.2	5.3	155	8.5	6.9	150	8.8	7.5	155	10.1	8.4	150
Fort Worth	4.8	3.0	155	4.8	3.6	140	5.5	4.7	150	5.8	5.5	150	6.8	6.6	155	7.2	6.9	150
Great Falls	2.8	1.5	152	4.2	2.5	141	5.6	4.0	154	5.7	4.9	150	6.7	6.0	155	8.3	6.9	150
Lake Charles	3.7	2.8	155	3.6	3.2	139	4.7	4.4	155	5.2	5.4	148	6.3	6.4	153	5.9	6.1	121
Madison	4.0	2.0	121	4.9	3.1	78	5.9	4.4	88	6.1	5.3	88	6.8	6.2	91	8.0	7.3	90
Medford	1.6	1.4	155	2.6	2.3	141	4.1	3.7	155	6.0	5.5	148	6.8	6.4	155	8.7	7.6	150
Miami	5.1	3.8	151	6.4	4.9	131	5.8	5.3	155	6.6	6.4	147	6.3	6.3	154	5.8	6.1	128
Nashville	3.1	2.1	155	3.6	2.9	142	4.0	3.6	153	5.6	5.3	146	6.3	6.3	125	6.1	6.3	150
New York	2.8	1.8	124	3.3	2.5	105	4.6	3.7	96	4.6	4.5	120	4.9	5.2	124	5.6	5.9	92
Omaha	4.6	2.4	155	5.1	3.2	131	5.4	4.2	117	6.3	5.4	127	6.5	5.9	149	7.0	6.6	107
Phoenix	5.8	3.6	155	6.5	4.5	141	7.9	6.0	137	9.3	7.5	143	10.0	8.4	153	9.3	8.1	150
Santa Maria	5.3	3.2	155	5.0	3.7	141	7.1	5.6	146	8.5	7.3	116	9.1	7.9	151	9.2	8.4	150
Seattle	1.5	1.0	155	2.0	1.7	141	3.7	3.1	155	4.8	4.4	150	6.0	5.8	155	7.6	6.6	150
Washington, DC	3.8	2.2	136	4.1	2.9	140	5.0	4.2	155	5.7	5.2	150	5.6	5.7	155	6.4	6.4	150

TABLE 1.3

MEAN DAILY TOTALS OF DIRECT-NORMAL
AND TOTAL-HORIZONTAL SOLAR RADIATION FOR JULY - DECEMBER

	July			August			Sept			Oct			Nov			Dec		
	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N	DN	TH	N
Albuquerque	9.2	8.1	153	9.2	7.6	127	7.9	6.2	147	7.8	5.1	153	6.6	3.8	150	6.1	3.2	155
Appalachicola	6.5	6.5	138	5.9	5.9	148	6.1	5.5	150	6.1	4.8	155	5.4	3.8	150	4.6	3.1	155
Bismark	8.7	7.0	155	8.1	6.3	146	6.7	4.6	150	5.7	3.2	155	3.9	1.9	150	3.5	1.5	155
Blue Hill	5.0	5.4	155	5.4	5.1	155	4.9	4.2	150	4.2	2.9	155	3.1	1.9	150	3.3	1.7	147
Boston	5.6	5.7	155	5.5	5.2	153	5.0	4.2	150	3.9	2.8	155	2.8	1.8	150	2.9	1.6	155
Brownsville	7.4	7.2	124	6.6	6.3	155	5.3	5.2	150	4.9	4.3	153	3.8	3.3	150	3.0	2.6	154
Cape Hatteras	8.2	7.5	137	7.1	6.5	155	7.1	5.8	132	5.7	4.2	133	4.9	3.2	150	4.5	2.7	155
Caribou	6.1	5.8	155	5.9	5.1	155	4.6	3.7	150	3.4	2.3	155	2.3	1.3	150	3.1	1.4	155
Charleston	5.4	5.9	153	5.4	5.6	154	5.2	4.9	150	5.3	4.2	146	4.3	3.1	145	4.0	2.7	153
Columbia	6.7	6.4	154	7.4	6.4	155	5.7	4.7	147	5.2	3.7	154	4.1	2.5	149	3.4	2.0	155
Dodge City	8.0	7.1	126	7.9	6.7	155	6.8	5.4	146	6.9	4.4	155	5.8	3.2	150	5.0	2.5	155
El Paso	8.7	7.8	155	8.7	7.4	155	7.7	6.2	150	7.7	5.3	155	6.4	4.0	150	6.1	3.5	155
Ely	8.8	7.6	155	8.6	7.0	155	8.4	6.1	150	7.4	4.6	155	6.0	3.2	150	5.6	2.7	150
Fort Worth	7.4	6.9	155	7.4	6.6	155	6.1	5.3	150	5.6	4.2	154	4.7	3.2	150	4.1	2.6	155
Great Falls	8.2	7.0	149	7.2	5.9	155	5.9	4.4	137	4.5	2.9	152	3.0	1.7	150	2.4	1.2	155
Lake Charles	5.6	5.8	151	5.1	5.3	152	5.0	4.9	150	4.7	4.0	154	4.0	3.1	142	3.3	2.5	155
Madison	7.8	7.0	93	7.4	6.3	93	5.8	4.5	83	4.7	3.1	93	3.4	1.9	90	3.8	1.8	93
Medford	9.8	8.1	155	8.4	6.8	155	6.6	5.1	150	4.4	3.2	153	2.4	1.8	150	1.4	1.1	155
Miami	6.0	6.3	155	5.8	5.8	155	5.2	5.1	150	5.8	4.8	155	5.2	4.0	150	5.2	3.7	155
Nashville	5.8	6.1	155	5.6	5.6	153	5.2	4.7	150	4.7	3.7	155	3.6	2.5	144	2.9	1.9	124
New York	4.7	5.3	91	4.3	4.6	116	5.3	4.5	95	4.0	3.0	93	2.6	1.8	88	2.8	1.6	91
Omaha	7.2	6.6	119	7.3	6.0	141	5.8	4.6	150	5.4	3.5	155	4.1	2.4	141	3.8	1.9	155
Phoenix	8.6	7.7	155	7.7	6.9	155	7.4	6.1	150	6.9	4.9	155	5.8	3.8	150	5.1	3.1	155
Santa Maria	8.5	7.9	155	7.9	7.0	155	7.2	6.0	147	7.0	4.9	155	5.7	3.6	150	5.1	3.0	155
Seattle	8.6	7.1	155	6.1	5.4	155	4.6	3.8	143	3.0	2.2	155	2.0	1.3	150	1.2	0.8	155
Washington, DC	5.5	5.9	155	5.5	5.4	155	5.2	4.6	150	4.7	3.5	153	3.6	2.3	150	3.6	2.0	155

and averaging over all five years. Days with missing data were simply omitted. Mean daily totals of total-horizontal solar radiation were calculated in the in the same way. All of these mean daily toals are given in Tables 1.2 and 1.3. In these tables, DN represents direct-normal solar radiation, TH represents total-horizontal radiation, and N is the number of days used in computing each mean.

The reader should bear in mind that these monthly mean availabilities are probably not completely accurate. They are based generally on data from five years of measurements, but these years may not be sufficiently representative. The period of record was chosen more on the basis of data availability and accuracy than on the basis of accurate representation. Data recorded during the late 50's has been judged to be generally more accurate than data recorded in earlier or later periods. Hopefully, studies like this one will be repeated as more reliable and more extensive data bases become available.

An interesting detail to be found in these tables is that DN nearly always equals or exceeds TH. This detail is brought out in Table 1.4, which shows the ratio DN/TH on a seasonal basis for each location. The ranges and average values of these seasonal ratios of direct-normal to total-horizontal are also given at the bottom of Table 1.4.

It is interesting that in the Spring and Summer these ratios are all generally just slightly above 1. This indicates that availability of total-horizontal radiation in these seasons is a reasonably accurate estimator of direct-normal radiation. Apparently, the gain in tracking represented in DN is generally slightly larger than the loss of the diffuse from the TH value.

The situation is not nearly so simple in the Fall and Winter. In these seasons the ratios are generally higher and more dependent upon location. Thus, a map of total-horizontal radiation would not accurately portray the availability of direct-normal radiation in these seasons. The suspicion of this was in fact one of the original motivations for this study.

TABLE 1.4

SEASONAL RATIOS, DN/TH, OF DIRECT-NORMAL AND TOTAL-HORIZONTAL SOLAR RADIATION

	Spring (M,A,M)	Summer (J,J,A)	Fall (S,O,N)	Winter (D.J,F)
Albuquerque	1.2	1.2	1.5	1.7
Appalachicola	1.1	1.0	1.2	1.4
Bismark	1.3	1.3	1.7	2.1
Blue Hill	1.1	1.0	1.4	1.7
Boston	1.1	1.0	1.3	1.6
Brownsville	0.9	1.0	1.1	1.1
Cape Hatteras	1.1	1.1	1.3	1.5
Caribou	1.2	1.1	1.4	2.0
Charleston	1.0	0.9	1.2	1.4
Columbia	1.1	1.1	1.4	1.6
Dodge City	1.2	1.1	1.5	1.8
El Paso	1.3	1.1	1.4	1.6
Ely	1.2	1.2	1.6	1.8
Fort Worth	1.1	1.1	1.3	1.5
Great Falls	1.2	1.2	1.5	1.8
Lake Charles	1.0	1.0	1.1	1.2
Madison	1.2	1.1	1.5	1.8
Medford	1.1	1.2	1.3	1.2
Miami	1.0	1.0	1.2	1.3
Nashville	1.0	1.0	1.2	1.4
New York	1.1	0.9	1.3	1.5
Omaha	1.2	1.1	1.5	1.8
Phoenix	1.2	1.1	1.4	1.6
Santa Maria	1.2	1.1	1.4	1.6
Seattle	1.1	1.2	1.3	1.3
Washington, DC	1.1	1.0	1.3	1.6
Range	0.9-1.3	0.9-1.3	1.1-1.7	1.1-2.1
Average	1.1	1.1	1.4	1.6

II. Solar Energy Availability Maps

The monthly means of TH and DN which are given in Tables 1.2 and 1.3 were used to produce maps displaying the monthly availabilities of total-horizontal and direct-normal solar radiation across the continental U.S. The maps showing the availability of direct-normal radiation are believed to be the first of their kind, although a few somewhat similar maps have been published before [3,4].

In order that these maps be free from subjective judgment, the contour drawing process was done with computer codes. Two codes were used. The first of these accepted the monthly mean daily totals and the latitudes and longitudes for the 26 sites as inputs. It produced monthly mean daily totals on a rectangular grid of location as output. This code was obtained from H. Akima of the Institute of Telecommunication Sciences, U.S. Department of Commerce, and the technique is described in [5].

The second code simply uses the regularly spaced values generated by the first code to provide a list of coordinates for points defining each isoline requested. Quite a few such codes are in existence; the particular one used was written by M. O. Dayhoff at the National Biomedical Research Foundation, Silver Springs, MD. The output from this second code was used to produce the maps manually.

One difficulty was encountered in the application of the first code to this task. The code is basically interpolative in nature. When asked to produce values for grid points geographically outside the area covered by the 26 input sites, the code would extrapolate to absurd values. This problem was solved by artificially creating 12 extra input data points surrounding the U.S. and about 1200 miles distant. After some comparisons indicated that this technique worked, and that the results were essentially independent of the values assigned to these created, remote sites, a value of 5 $kW \cdot hr/m^2$ was assigned to each of these sites in every case.

These maps showing monthly means of daily totals of TH and DN are given in Figures 2.1 through 2.12. A comparison of the TH maps produced by this study with the monthly TH maps published by the Environmental Data Service of NOAA [6] shows that they are quite similar. In some cases the maps look different, but attempts to "read" the maps to produce TH radiation values at sites not on isolines reveal that the maps are not substantially different. A comparison of the winter TH maps with the winter DN maps indicates that TH maps in the winter do not provide an an accurate picture of solar energy availability. Another interesting point is that in every month there is generally more direct-normal than total-horizontal. This suggests that concentrating collectors might be more widely applicable geographically then was previously believed. This is especially important for summer cooling where higher fluid temperatures are required and where there is probably a high correlation between direct-normal radiation and cooling loads. This is also of interest because concentrating collectors may prove cheaper to build and more efficient than flat-plate collectors.

III. Correlation between Mean Daily Totals of Direct and Total Radiation

The data used to construct the tables and maps of the previous two sections consisted of hourly values of TH and DN over a five-year period. The values of TH were actual readings, while the values of DN were computed as described in Section I. These computations were performed on an hourly basis, and it is generally believed that estimating DN from TH on an hourly basis can be reasonably accurate because the geometry doesn't vary too much during one hour.

After these values of DN have been summed to produce monthly mean daily totals, it is natural to ask whether there is any correlation between these mean daily totals of TH and the mean daily totals of DN. If such a correlation could be established, it would permit the calculation of mean daily totals of DN for all those additional sites for which only daily totals of TH are available.

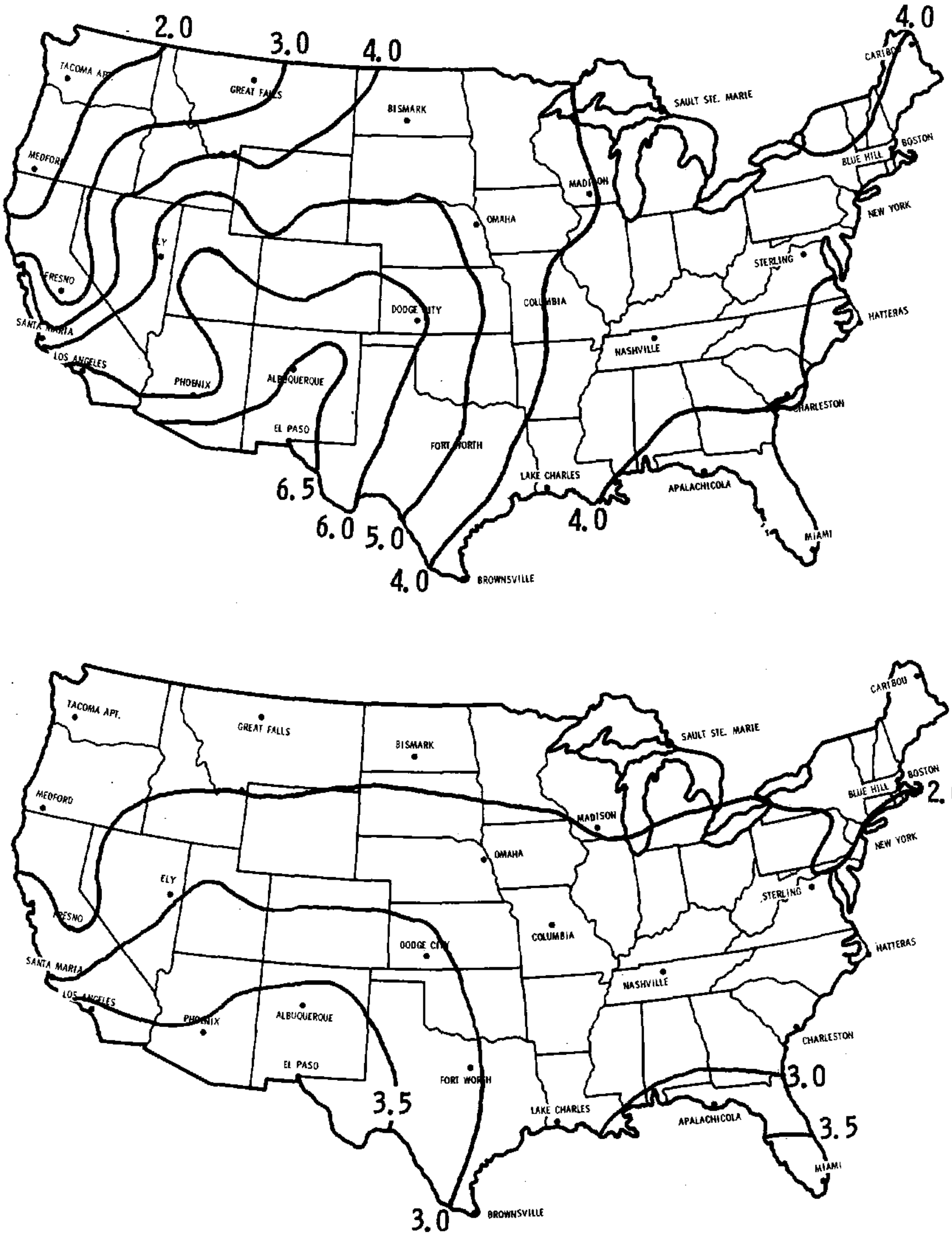


FIGURE 2.1. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR JANUARY (kW · hr/m^2)

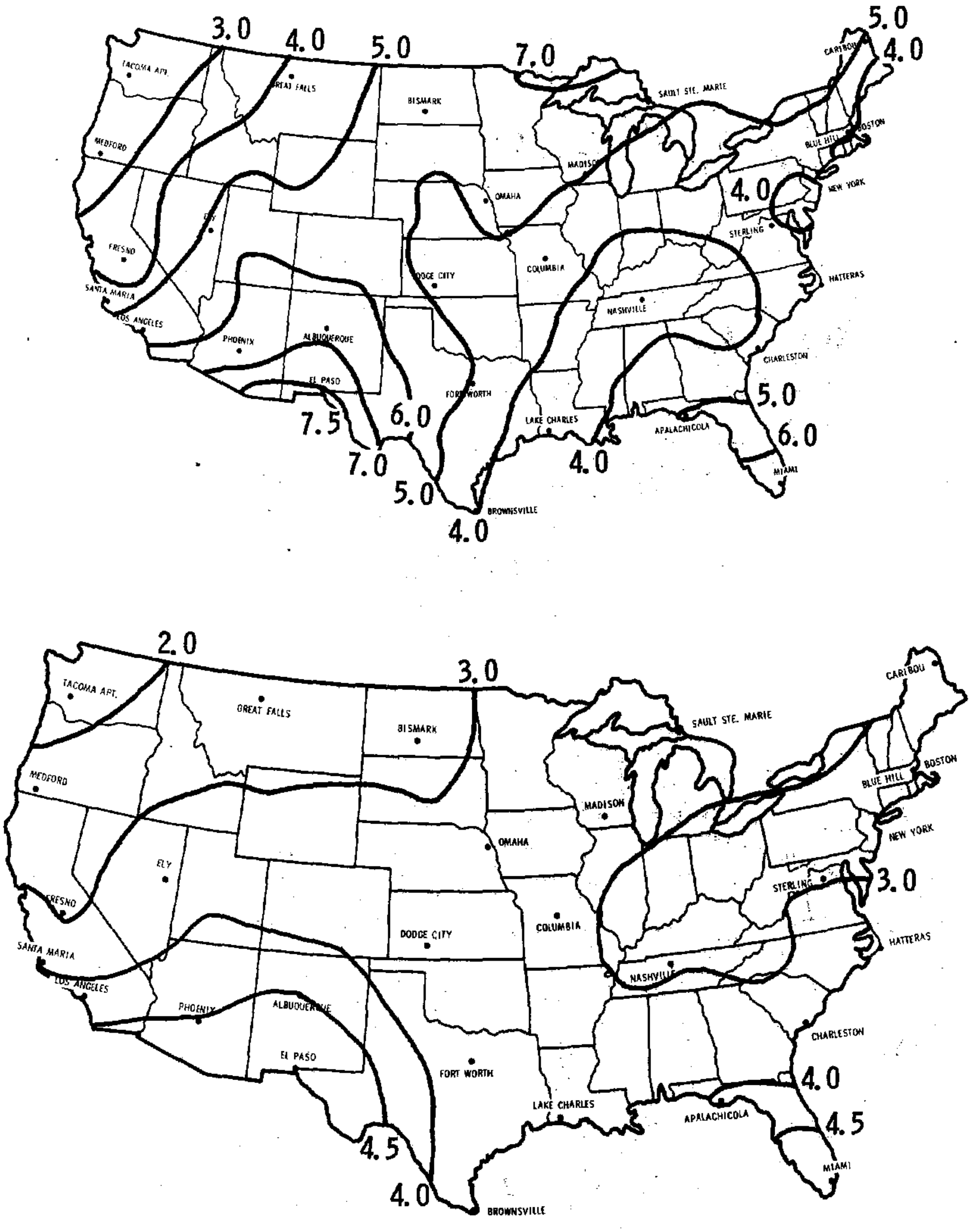


FIGURE 2.2. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR FEBRUARY ($kW \cdot hr/m^2$)

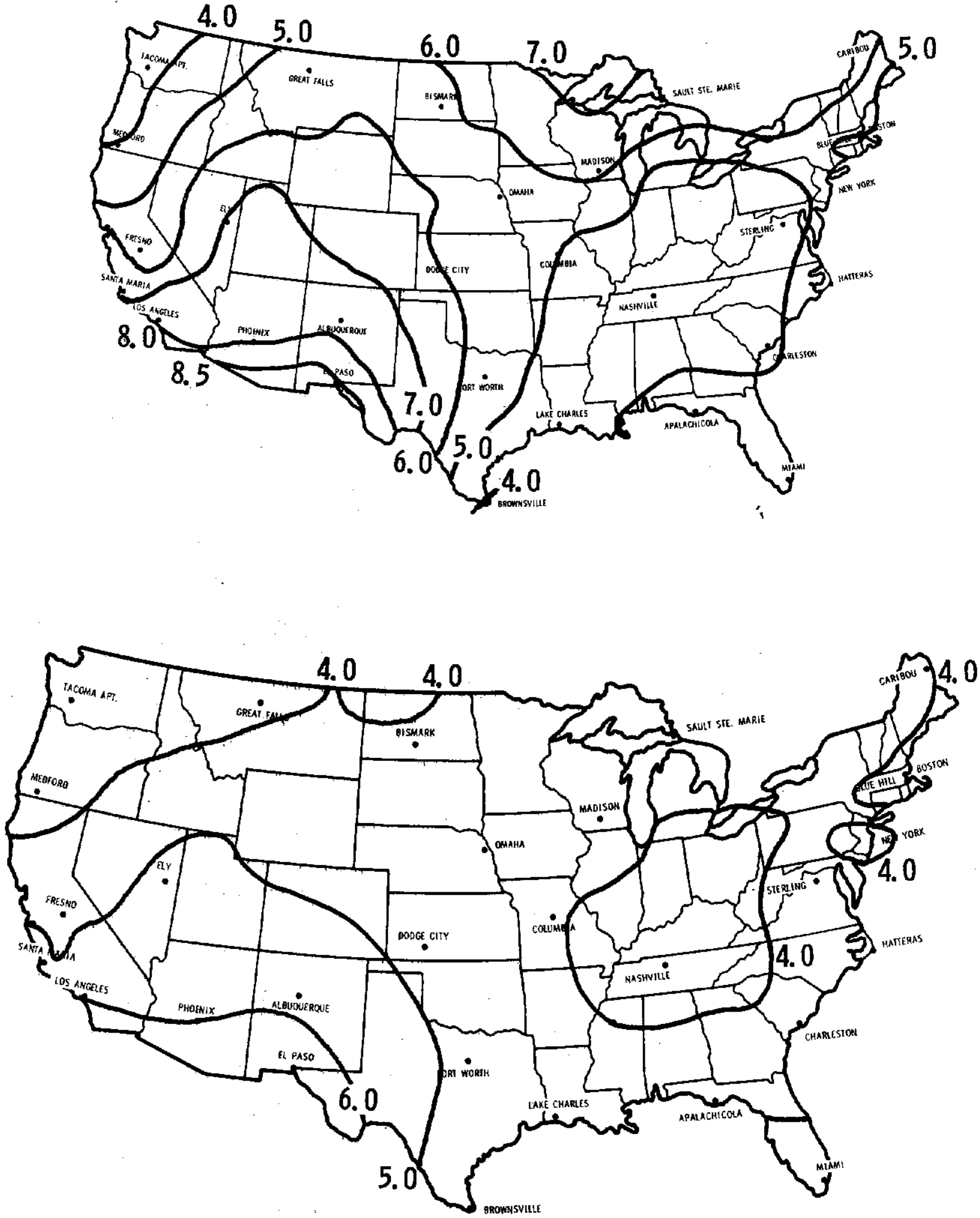


FIGURE 2.3. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR MARCH ($kW \cdot hr/m^2$)

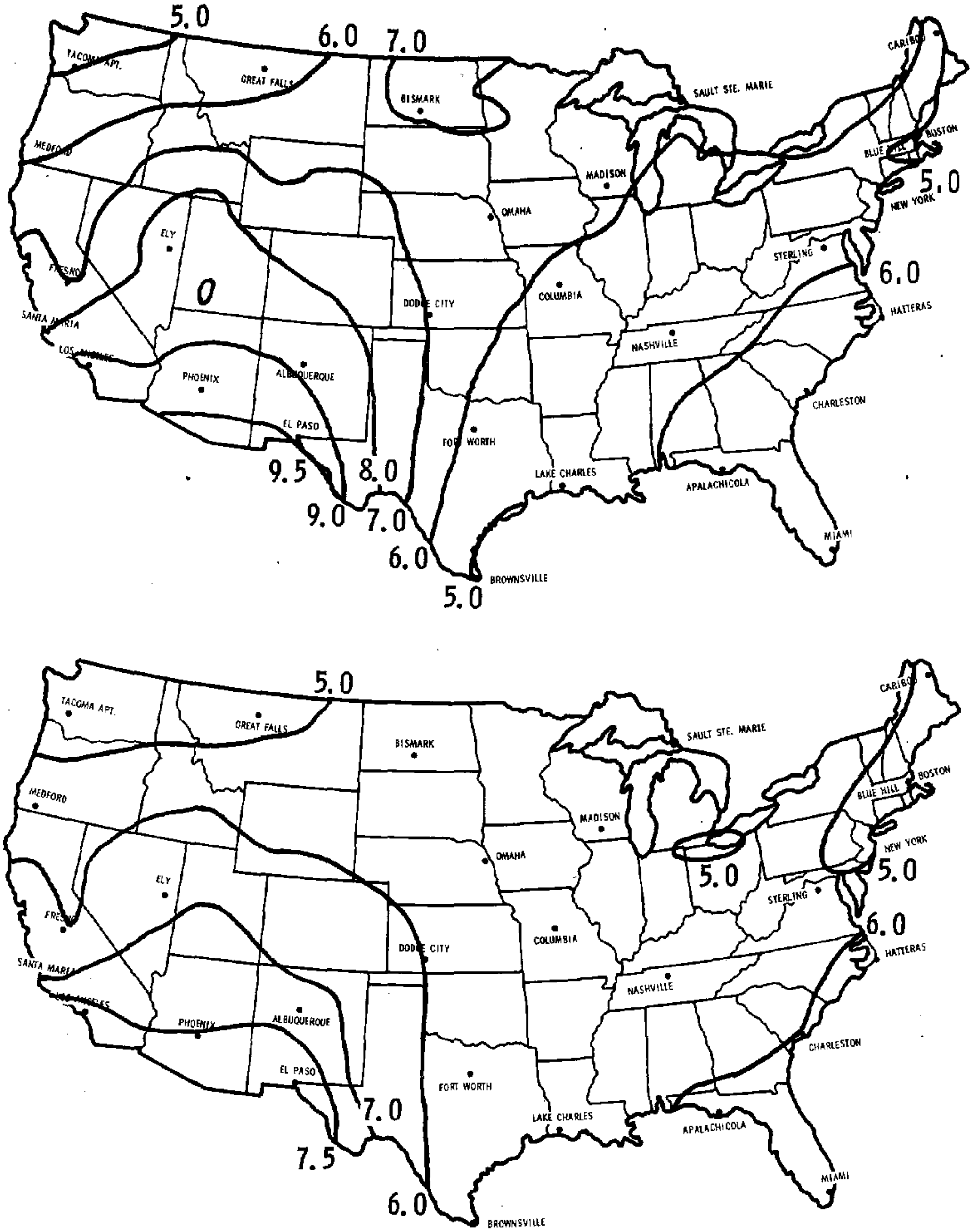


FIGURE 2.4. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR APRIL ($kW \cdot hr/m^2$)

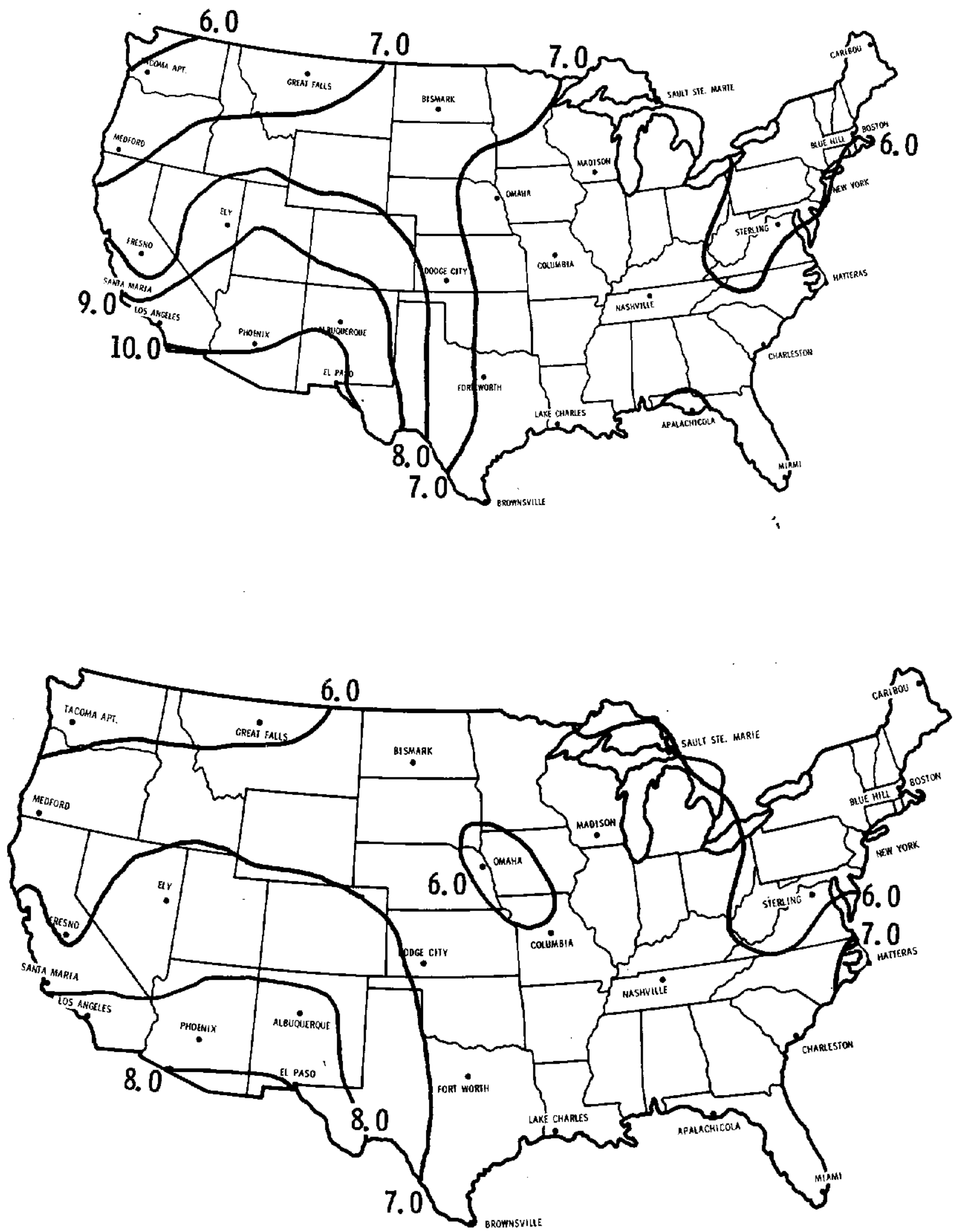


FIGURE 2.5. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR MAY ($kW \cdot hr/m^2$)

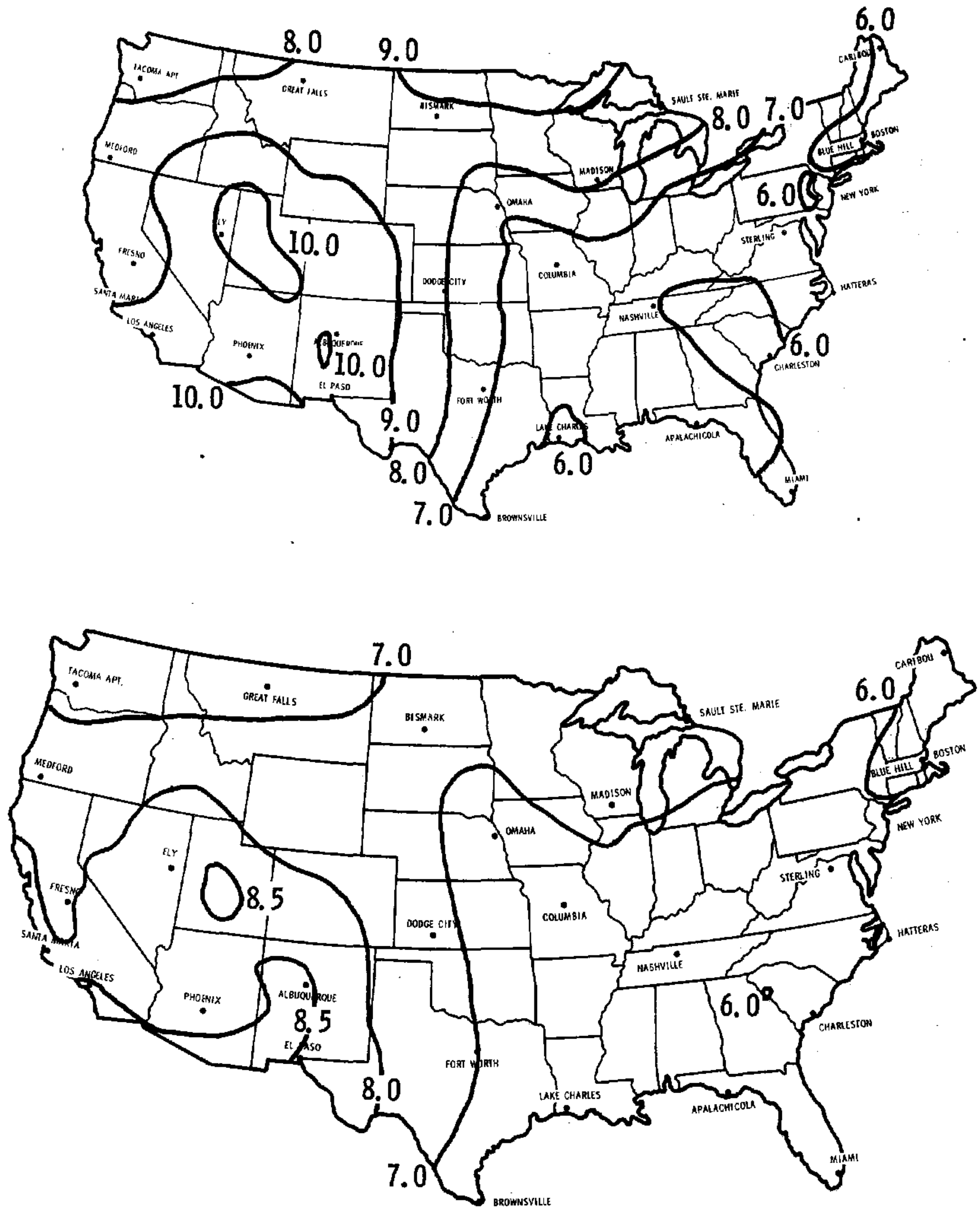


FIGURE 2.6. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR JUNE ($kW \cdot hr/m^2$)

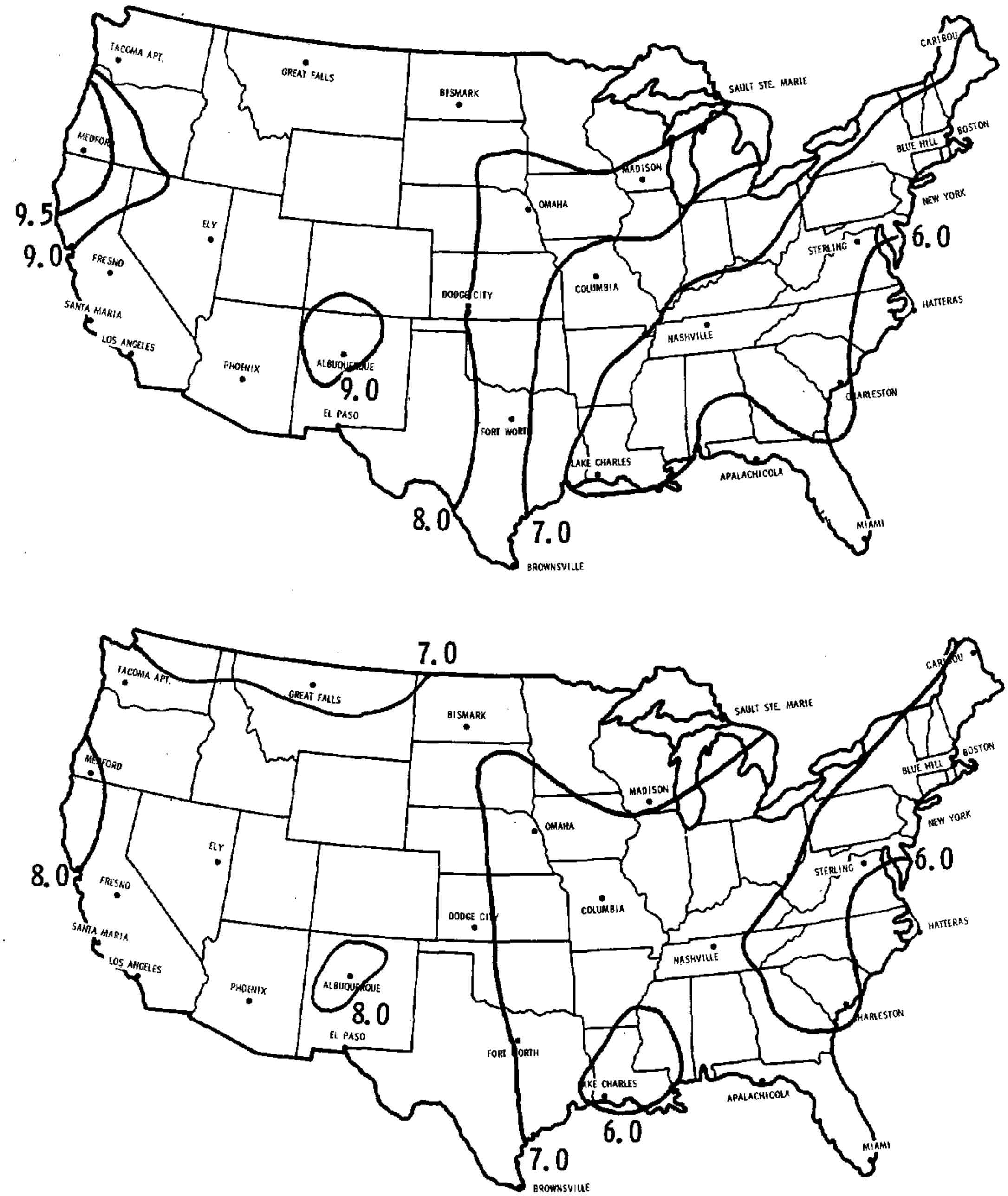


FIGURE 2.7. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR JULY ($kW \cdot hr/m^2$)

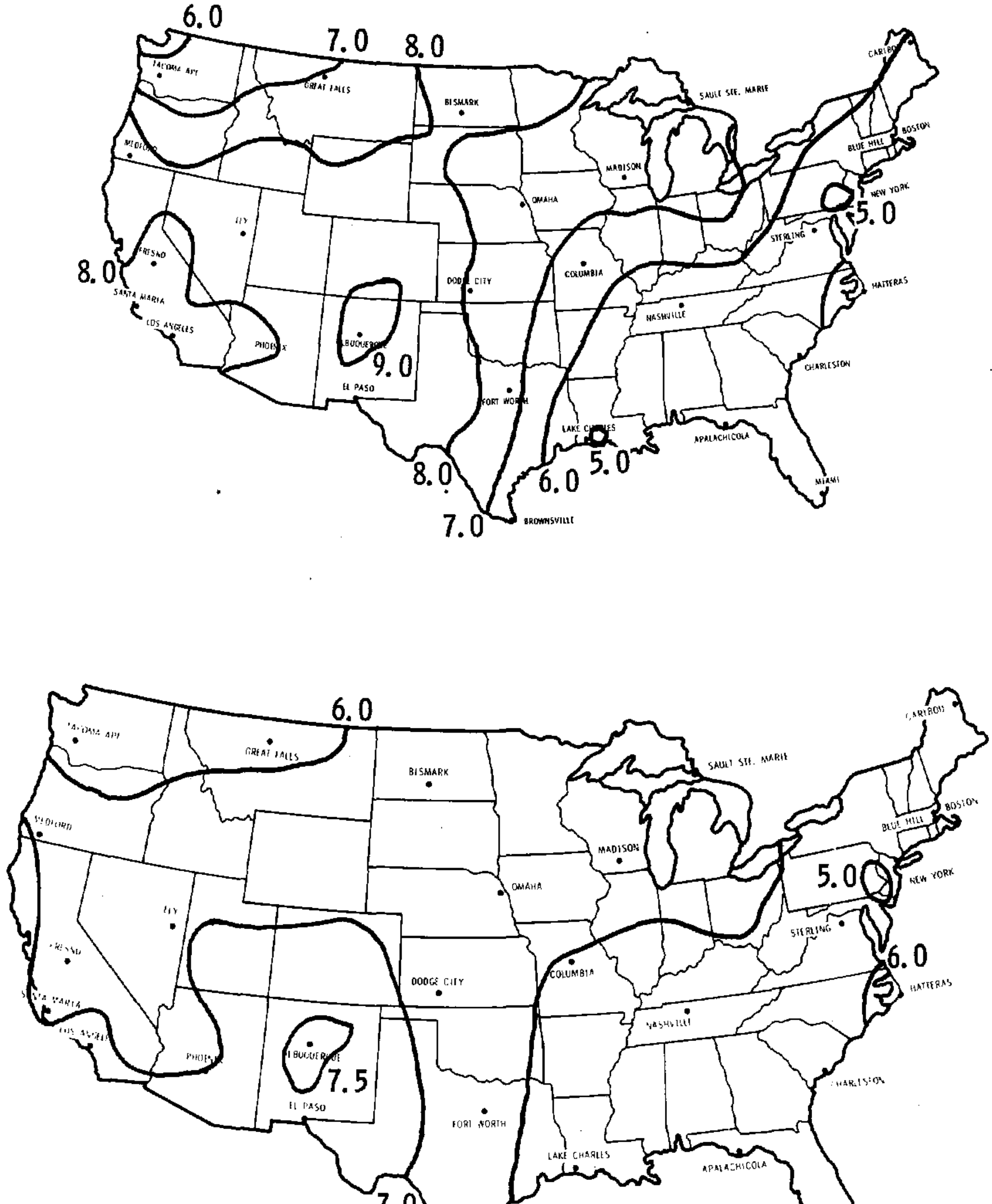


FIGURE 2.8. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR AUGUST ($kW \cdot hr/m^2$)

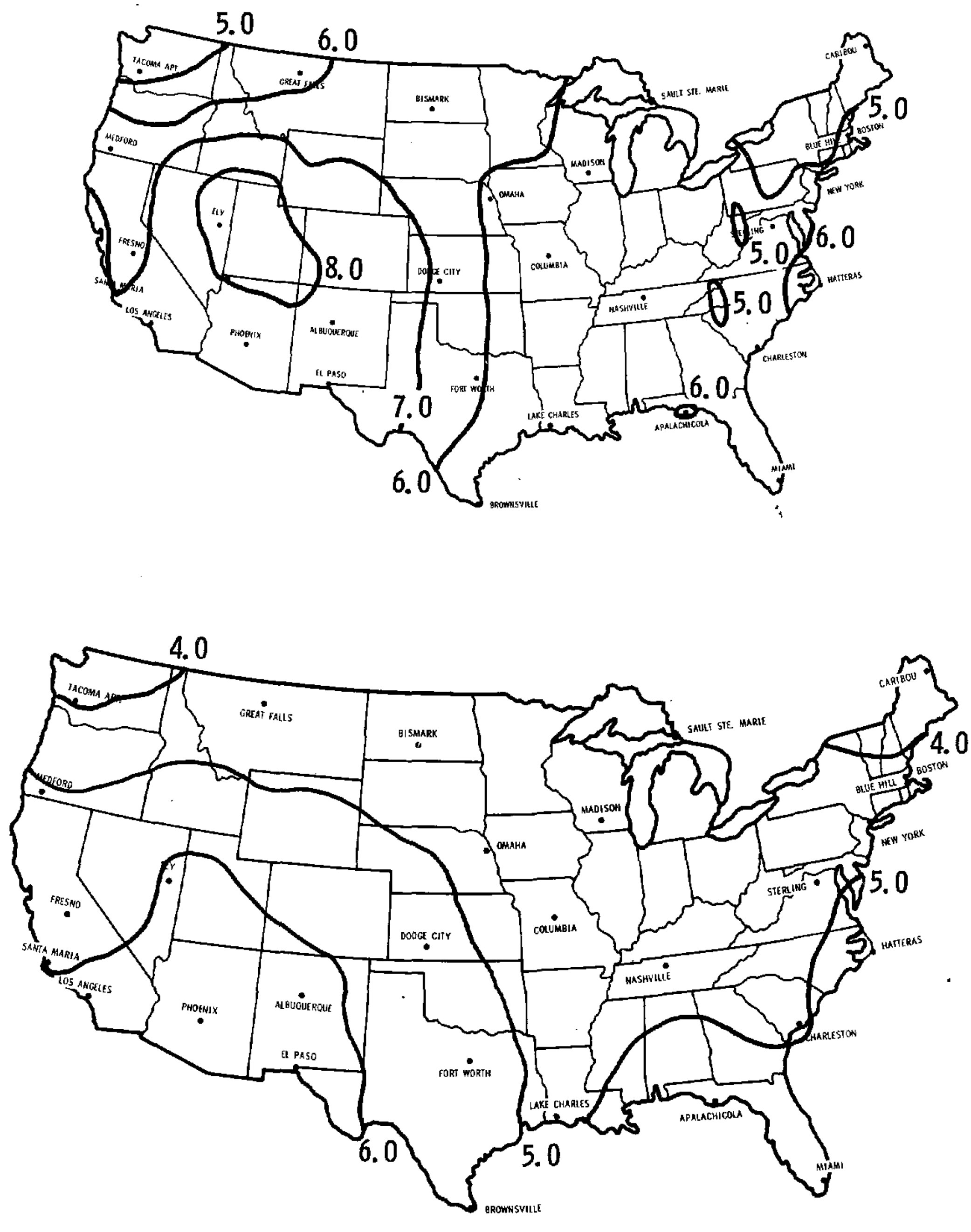


FIGURE 2.9. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR SEPTEMBER (kW · hr/m^2)

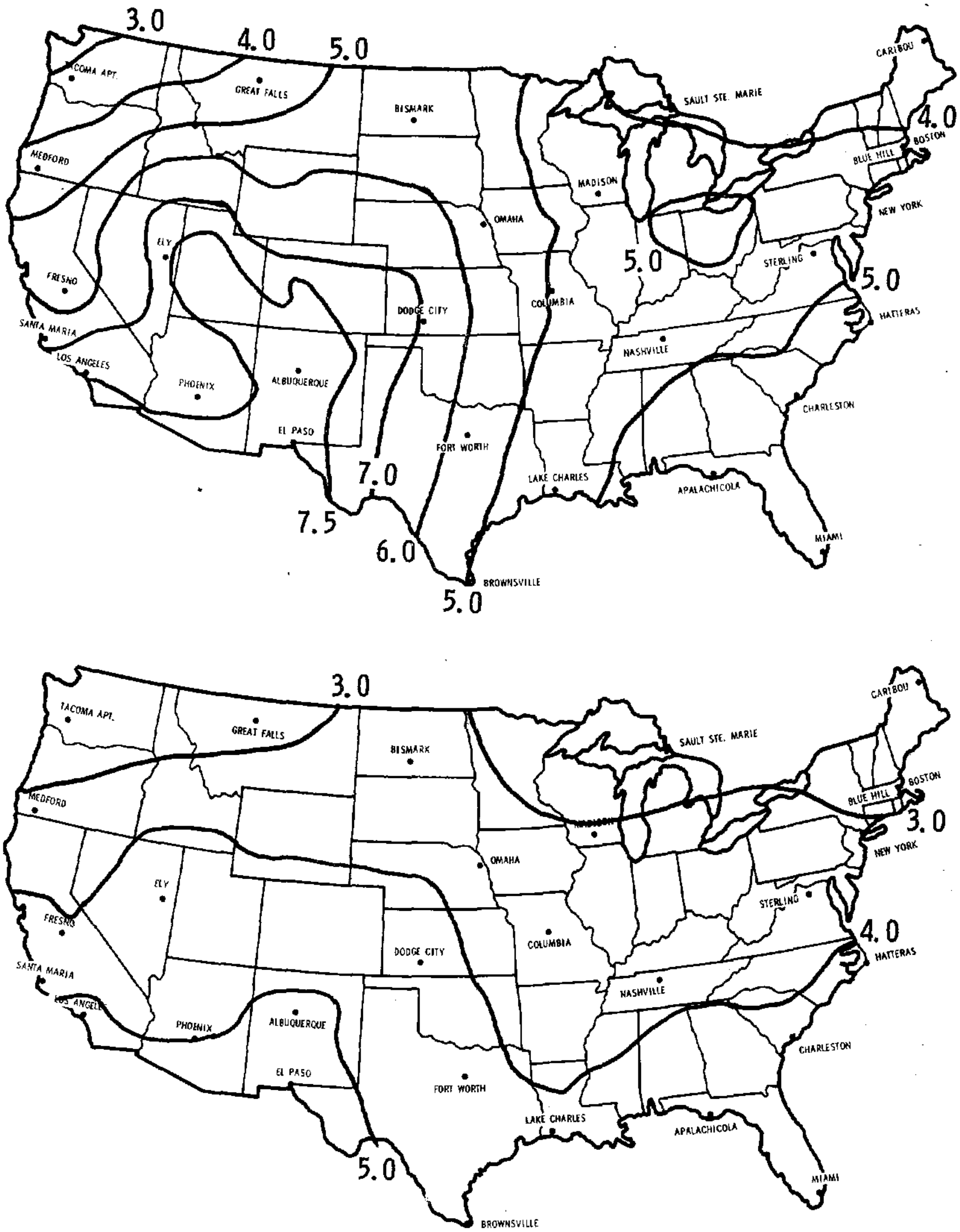


FIGURE 2.10. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR OCTOBER ($kW \cdot hr/m^2$)

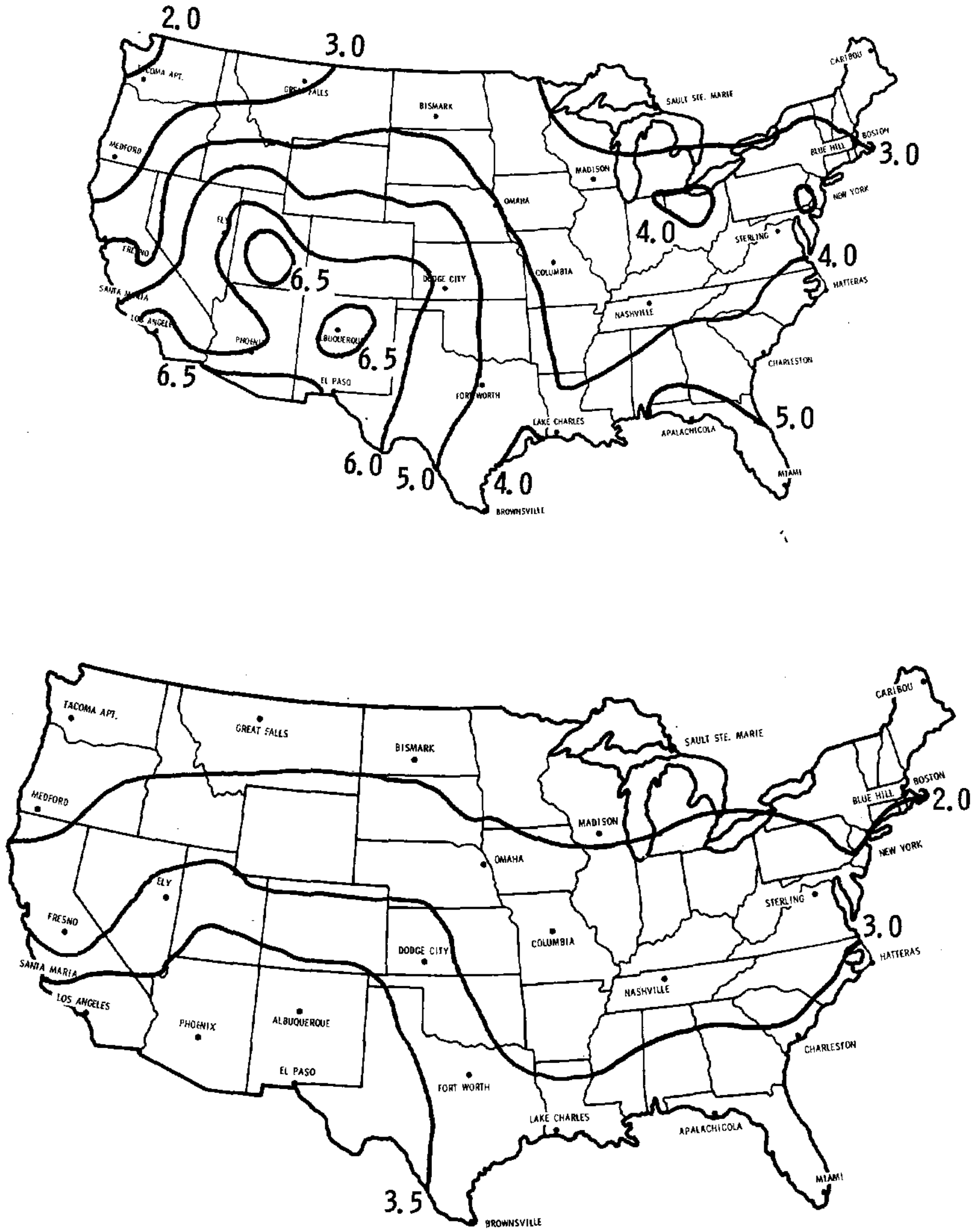
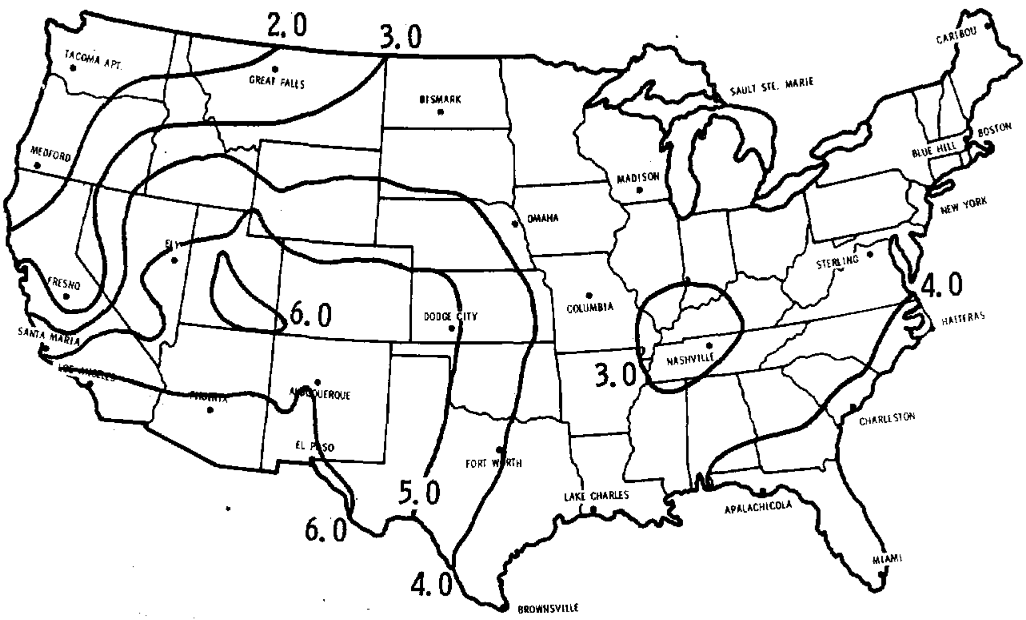


FIGURE 2.11. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR NOVEMBER (kW · hr/m^2)



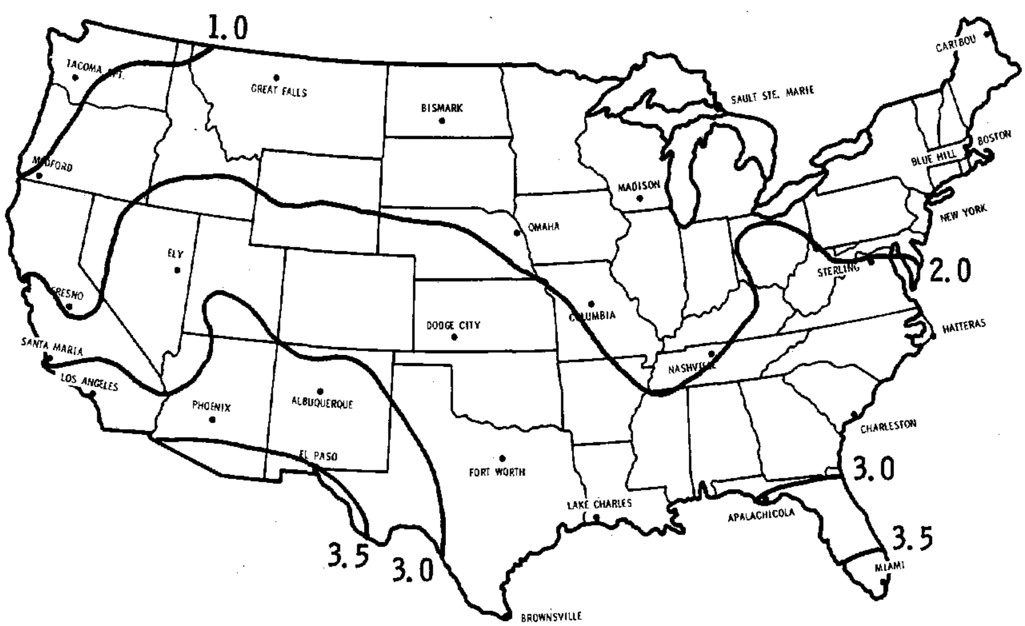


FIGURE 2.12. MEAN DAILY DIRECT-NORMAL (TOP) AND TOTAL-HORIZONTAL (BOTTOM) SOLAR RADIATION FOR DECEMBER (kW · hr/m^2)

In order to see if such a correlation between monthly means of daily totals of TH and DN exists, these were plotted for the months of January and July in Figures 3.1 and 3.2. Each point represents the mean daily total of TH versus the mean daily total of DN for one location. As one would expect, the data for January is considerably more scattered; this is due at least in part to the fact that the cosine effect in TH is affected a great deal more by latitude in the winter. One can easily see this by recalling that on an instantaneous basis,

(3.1) $\quad TH = DN \cos \theta + \text{diffuse},$

where θ is the sun's zenith angle and the diffuse is on the horizontal. In the winter θ is generally a much larger angle and so θ's dependence upon latitude produces a larger change in $\cos \theta$.

In an attempt to reduce the dependence on latitude, equation 3.1 was rewritten in the form

(3.2) $\quad TH = DN \cos (\text{Lat} + 20^\circ) + \text{diffuse}$, for January.

This equation is valid at solar noon when the declination is -20° which would occur in mid-January. In Figure 3.3, the values of DN are plotted versus TH/cos (Lat +20°) for January for the 26 sites. Clearly, this adjustment has vastly reduced the scatter of the data in Figure 3.1. The values of DN are plotted versus TH/cos (Lat -20°) for July in Figure 3.4; here, the improvement is not so obvious. In each of the Figures 3.1 - 3.4, the regression equation, standard error of estimate, S, and correlation coefficient, R, are given.

Probably the highest correlation would be obtained by plotting DN versus TH/cos θ where θ represents an "average" zenith angle for a month at a site, computed as a function of both time and air mass. In any case, this seems to be a promising area for further study, especially when more and better data becomes available.

FIGURE 3.1

January

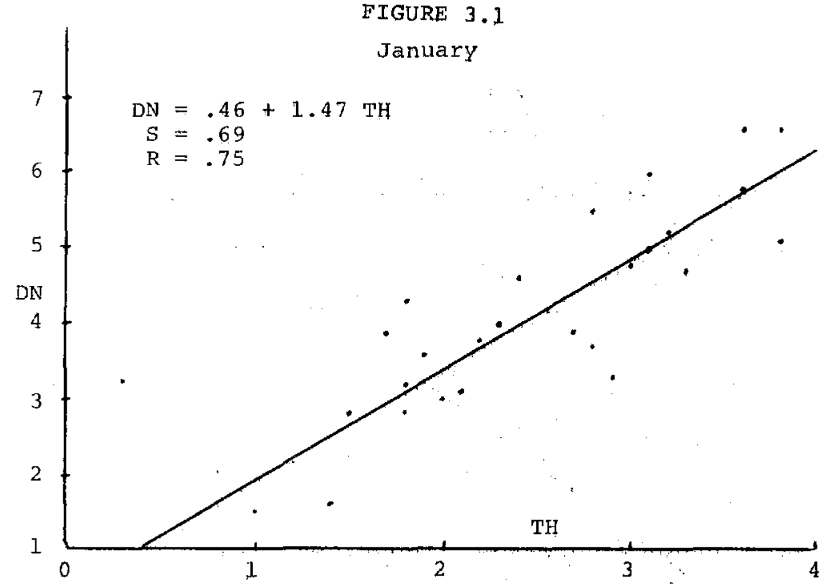


FIGURE 3.2

July

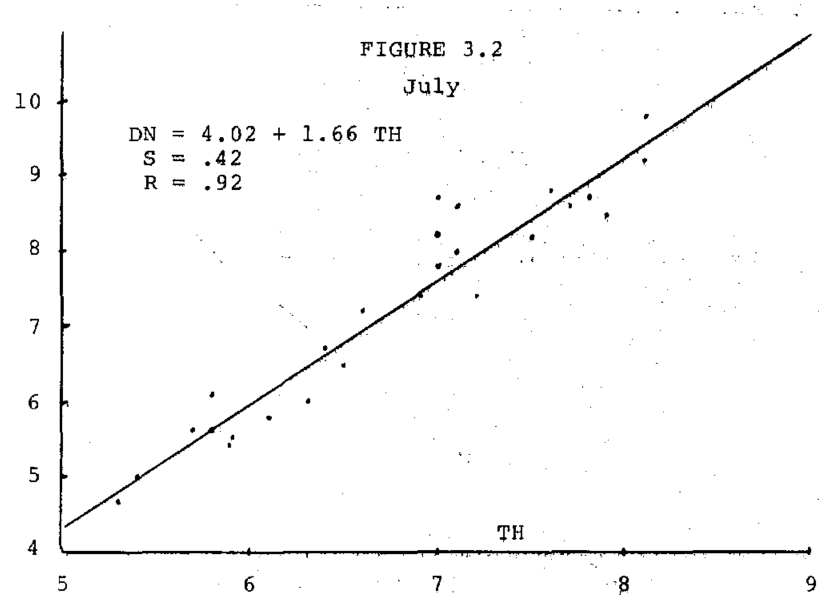


FIGURE 3.3

January

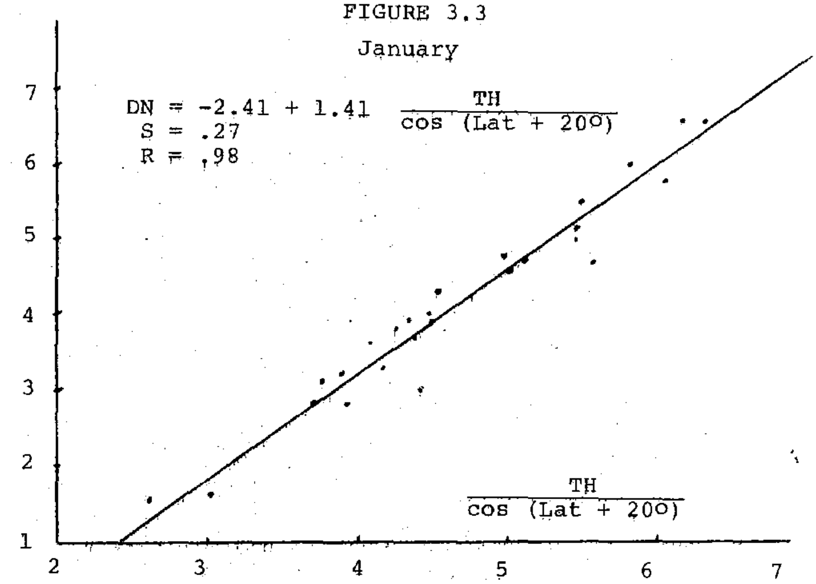
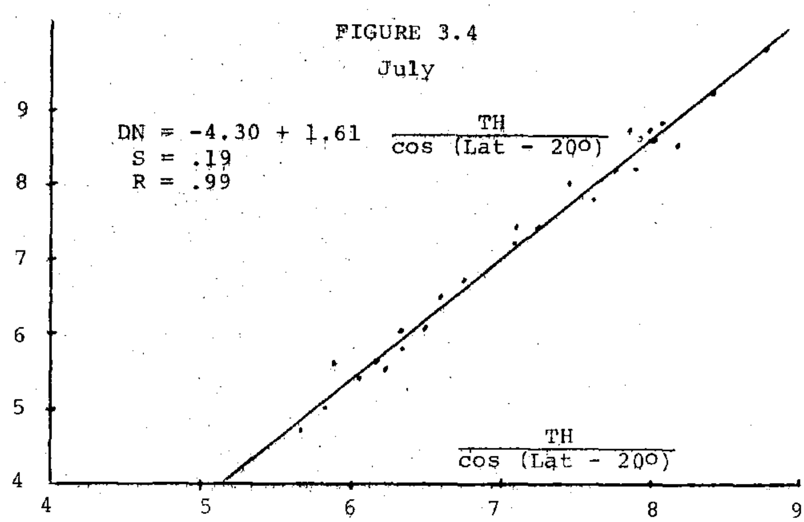


FIGURE 3.4

July



REFERENCES

1. E. Boes, "Estimating the Direct Component of Solar Radiation," Sandia Laboratories Report SAND75-0565.

2. R. Jordan and B. Liu, "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation," Solar Energy, IV, p. 1, 1960.

3. R. W. Palm, "Selecting Preferred Sites for a Solar Power Station Using Solar/Climatic Data," Report by Honeywell, Inc. for NASA, June 1974, NASA CR-134667, 7203-3301(A).

4. W. Mingenbach, "Solar Energy Climatic Analysis," The Architects, Taos, November 1975, Taos, NM; also available from Sandia Laboratories, Albuquerque, NM

5. H. Akima, "A Method of Bivariate Interpolation and Smooth Surface Fitting for Values Given at Irregularly Distributed Points," OT Report 75-70, August 1975, US Dept. of Commerce.

6. "Climatic Atlas of the United States," June 1968, Environmental Data Service, ESSA, US Dept. of Commerce.

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